



# FORWARD PROJECTIONS

## CROATIA

Cross-border river demo Croatia-Serbia



**SUPERB**  
Upscaling Forest Restoration



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036849.

## Author(s)

**Sara Filipek<sup>1</sup>, Silke Jacobs<sup>1</sup>, Gert-Jan Nabuurs<sup>1</sup>, Barbara Škiljan<sup>2</sup>, Martina Đodan<sup>2</sup>**

## Acknowledgment

**The Croatian National Forest Inventory; Jura Čavlović<sup>3</sup>**

## Affiliations

<sup>1</sup>Wageningen Environmental Research, Droevendaalsesteeg 3a, 6708 PB Wageningen, The Netherlands

<sup>2</sup>Croatian Forest Research Institute, Cvjetno naselje 41, 10450, Jastrebarsko, Croatia

<sup>3</sup>University of Zagreb, Faculty of Forestry and Wood Technology, Department of Forest Inventory and Management, Croatia

## Recommended citations

Filipek S., Jacobs S., Nabuurs GJ., Škiljan B., Đodan M. 2025. Deliverable D6.5: The Croatian side demo forest development under varying restoration scenarios projected until 2055. Horizon 2020 project SUPERB, project no. 101036849, Wageningen Environmental Research.



# Contents

<b>EXECUTIVE SUMMARY</b>	<b>3</b>
<b>DEMO INFORMATION</b>	<b>4</b>
<b>MODEL DESCRIPTION</b>	<b>5</b>
EFISCEN-SPACE MODEL	5
<b>SCENARIO DESCRIPTION</b>	<b>6</b>
EFISCEN-SPACE SCENARIOS	6
1. BASELINE (BAU)	7
2. RESTORATION SCENARIO #1 – REPLACEMENT OF <i>POPULUS</i> PLANTATIONS	7
3. RESTORATION SCENARIO #2 – DIVERSIFICATION OF <i>QUERCUS</i> FORESTS AND INVASIVE SPECIES REDUCTION	7
<b>PROJECTION RESULTS</b>	<b>9</b>
EFISCEN-SPACE	9
<i>Growing stock</i>	9
<i>Increment</i>	10
<i>Harvest</i>	11
<i>Mortality</i>	12
<i>Gini index</i>	13
<i>Soil organic carbon</i>	14
<b>KEY FINDINGS</b>	<b>15</b>
<b>RECOMMENDATIONS</b>	<b>16</b>
<b>REFERENCES</b>	<b>17</b>



# EXECUTIVE SUMMARY

Forest restoration initiatives are becoming widespread in many European countries. Within these initiatives, attempts are being made to restore various forest habitat types and a wide range of areas with different socioeconomic and ecological backgrounds. Forest restoration goals in Europe may not always align with those of historical reference forests, as climate change increasingly makes such restoration unfeasible. As a result, objectives are often redirected toward managed forest states that support the continual provision of desired goods and ecosystem services. Therefore, the most likely trajectories of future forest development are needed to assess and evaluate restoration outcomes, as well as advise on successful measures which could support upscaling of the restoration initiatives.

This Croatian side of the cross-border demo projection report is part of the deliverable D6.5 on projected ecosystem data. The forest development under varying restoration scenarios is projected for the upcoming 30 years, till 2055 using the EFISCEN-Space model.

The model projections showed that (1) replacement of *Populus* plantations does not have immediate positive effects on the development of the forest resources e.g. growing stock volume, increment and structural diversity, (2) diversification of *Quercus* sp. dominated forests but underplanting measures has overall positive effect on the structural forest complexity and soil organic carbon (SOC) stocks, (3) development of forests under all three scenarios becomes stable from 2045 onwards which means that to maintain further development of resources and structural diversity, forest management needs to consider both cuttings and underplanting which could regulate and sustain the resources in the long-term, (4) the 92 800 hectare of forest restoration area may costs around 464 million Euro (at average hectare costs of 5 000 Euro; see Croatia-Serbia cross-border workplan v2.0).



# DEMO INFORMATION

The cross-border demo area across Croatia and Serbia is characterized by riparian forests closely associated with groundwater and seasonal inundation, showcasing a diverse range of forest types. The Serbian segment of the demo lies within the protected Biosphere Reserve "Gornje Podunavlje", while the Croatian part features fragmented forests, mainly comprising non-native poplar clones, nestled amidst alluvial and eugley-amphigley soils surrounded by intensive agricultural land (Figure 1). Notably, several Croatian stands fall under the Natura 2000 network. The restoration efforts in the Serbian segment encompass approximately 28 hectares, while various pilot cases in both Serbia and Croatia, ranging from individual stands to larger landscapes up to 1000 hectares, are being considered for restoration. Croatia has witnessed successful restoration of around 1000 hectares of similar stands over the last three decades, with an additional 2000 hectares earmarked for potential restoration. Two restoration sites in Croatia, totaling 53.5 hectares, are scheduled for restoration across two seasons. This cross-border demo is surrounded by fragmented agricultural land interspersed with patches of forest, meadows, and pastures, overseen by different management entities such as Public Enterprise Croatian Forests Ltd. in Croatia and , "Vojvodinašume" in Serbia along with private forest owners.

In this deliverable, we only project the Croatian side of the cross-border demo due to lack of National Forest Inventory (NFI) data for Serbian part of the demo.

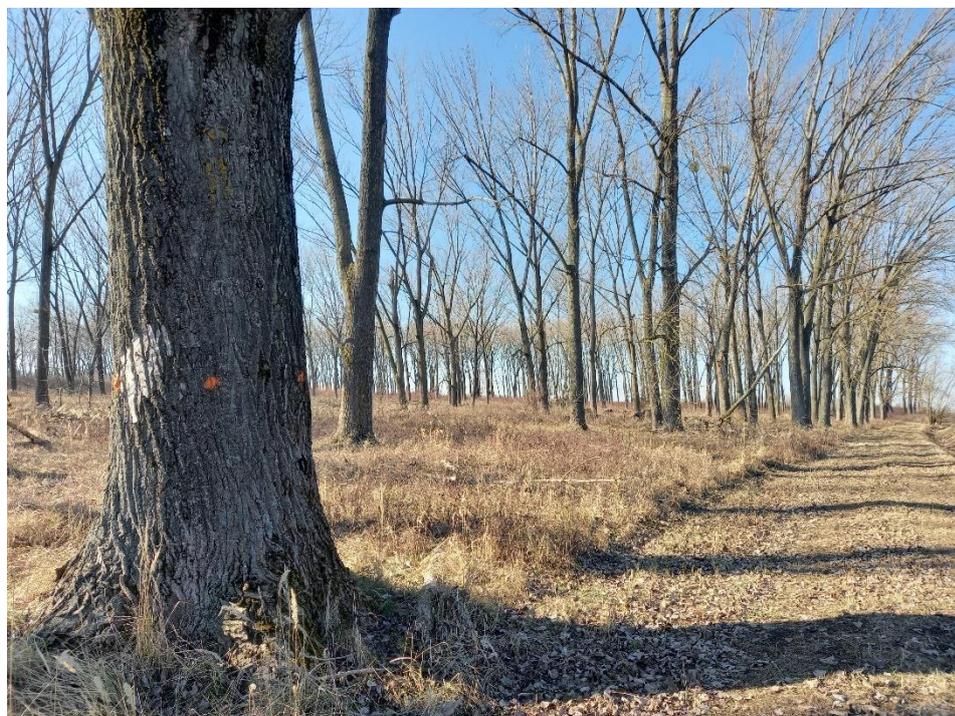


Figure 1. Landscape and internal appearance of *Populus* dominated forests.

# MODEL DESCRIPTION

## EFISCEN-Space model

EFISCEN-Space is an empirical European forest model that simulates development of forest resources under varying scenarios of forest management and climate change. It keeps track of the development of the diameter distribution of 20 tree species (groups) for individual plot locations (Schelhaas et al., 2022). The diameter distribution changes over time due to the growth of trees (simulated by the growth of trees to a larger diameter class), the removal of trees due to natural (background) mortality or harvest, and the occurrence of new trees (ingrowth) in lowest diameter classes. The EFISCEN-Space model is initialized on tree-wise observations from forest inventories, usually National Forest Inventories (NFIs), and driven by environmental datasets with pan-European coverage (Nabuurs et al., 2007, Schelhaas et al., 2022, Filipek et al., In prep). This data are used to initialize forest structure and are the basis for the model's detailed and dynamic (i.e. sensitive to forest structure) simulation of growth (Schelhaas et al., 2018). Growth is related to the current forest structure (plus the abiotic predictors), and as incorporated here under a RCP 4.5. scenario for all baseline (BAU) and restoration scenarios. As the growth functions are fitted on repeated NFIs with a wide range of sites and weather data this results in a climate sensitive growth function. EFISCEN-Space is not a process based model, but it incorporates climate sensitivity by linking its growth functions to annually downscaled weather data from the MPI-ESM1-2-LR global climate model under RCP 4.5. This means forest growth responds to the projected climate changes.

Planting, thinning and final cut can be carried out in EFISCEN-Space according to specified regimes. Natural mortality and harvesting can both be based on fixed regimes (based on repeated forest inventories), and on dynamic modules for natural mortality and ingrowth and simulating harvest using harvest rule patterns. Dynamic modules for mortality and ingrowth are both fitted on large sets of repeated NFI plots and tree wise data (Schelhaas et al in prep; König et al., 2025).

Model outputs provide information about forest resources (growing stock volume, increment, harvested volumes, biomass), carbon pools (biomass, litterfall and soil), biodiversity (number of large size trees, species composition, Gini index, deadwood).

# SCENARIO DESCRIPTION

## EFISCEN-Space scenarios

For the baseline (BAU) and two restoration scenarios we used the subset of Croatian NFI-1 (2005–2009). In total we simulated 456 plots which represented 182 400 ha of forest area (7% of total Croatian forest area; Figure 2). As the model was initialized on the latest processed Croatian NFI-1 data, the model was first simulated to year 2025 with current observed rule management to account for the forest development until 2025. Then the state of the forest in 2025 was used to re-initialize and simulate demo from this common point in time until 2055 for each scenario.

As forest restoration measures need to be adaptive to climate change, both baseline and restoration scenarios were simulated under climate change scenario RCP4.5 (MPI-ESM1-2-HR). To represent forest dynamics, dynamic ingrowth and mortality were applied to all scenarios.

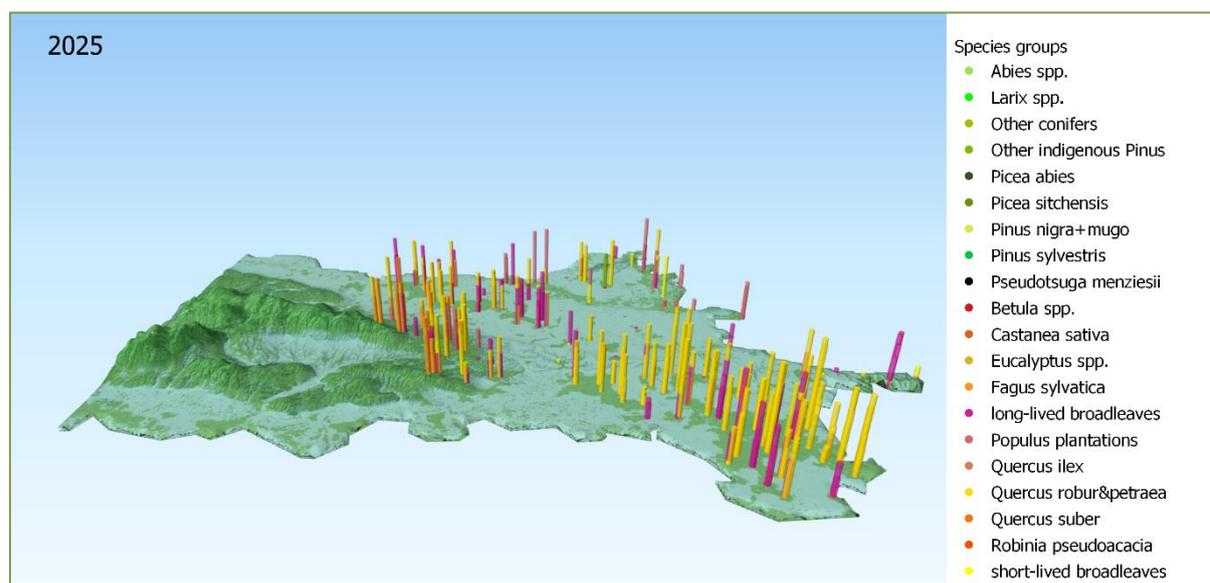


Figure 2. Map of initialized NFI plots in Croatian side of the cross-border demo, in total 456 plots. Colour of the bar represents the initial dominant species or species group per plot, and the height of the bar shows the initial growing stock volume (the higher the bar, the larger the growing stock volume).

## 1. Baseline (BAU)

Baseline (BAU) scenario simulated development of forest resources under current forest management. The current forest management was based on observed German harvest rule patterns, and Slovak volume functions, due to lack of this information from Croatian data. The harvest rule patterns were described by two types of cutting types: thinning and final felling. The rules patterns were defined by a set of rules which included information about tree species, tree diameter class, stand basal area, number of trees per hectare, country and biogeographical region where forest stand was located (Filipek et al., in prep; Feliciano et al., 2025). Each rule pattern included information about the probability of cutting, its intensity (e.g. amount of basal area removed from the forest stand) and its type (e.g. thinning from below or from above, which emphasis cuttings of different cohorts of the forest stand diameter distribution).

## 2. Restoration scenario #1 – Replacement of *Populus* plantations

The replacement of *Populus* plantations implements transformation of Poplar plantations into mixed *Quercus* dominated forests with additional admixture of species like *Sorbus* spp. and *Prunus avium*. As *Populus* forests are highly sensitive to abiotic and biotic factors like wind, changes in ground water table level and diseases, the replacement of those forests will be necessary in the future due to foreseen impacts of climate change on these ecosystems. Especially replacement of non-native *Populus* species which are more vulnerable than the native *Populus* species. Although if water table levels remain beneficial for *Populus* species, the current forest composition will be maintained with regular forest management. In case the water table level will decrease significantly, to the level that it is not suitable for growth of *Populus* species, the transition to *Quercus* and other broadleaved species will be necessary.

To simulate this scenario, we identified the forests dominated with *Populus* located on calcaric fluvisols soils (in total 20 plots that represent 8000 ha of total forest area) which are highly susceptible to changes in the groundwater table levels. To facilitate the replacement of selected *Populus* dominant forest on the calcaric fluvisols soils, we increased thinning intensity of forest stands with basal area above 25 m<sup>2</sup>/ha by 30% and intensity of the final fell cutting to 100%. Then we underplanted these Poplar dominated stands with native *Quercus* spp., *Sorbus* and *Prunus avium* species every 5 years, with planting densities of 5000 trees/ha and 200 trees/ha respectively. As a result, we expected that the replacement of vulnerable *Populus* plantations would promote a more diverse and resilient floodplain forest ecosystem.

## 3. Restoration scenario #2 – Diversification of *Quercus* forests and invasive species reduction



To strengthen biodiversity and resilience in existing native *Quercus* dominated forests, the restoration measures need to consider diversification of forest structure and species compositions. As the native species are threatened by extensive growth of invasive species of trees and plants e.g., *Fraxinus pennsylvanica*, *Acer negundo*, *Reynoutria japonica*, the abundance of invasive species needs to be carefully monitored and regulated when necessary. The invasive species thrive in open areas under direct sunlight. Therefore maintaining forest canopy cover through shelterwood system is preferable to maintain mature oak dominated forests with understory composed of species like *Sorbus* and *Prunus avium* which support forest diversification.

To simulate this scenario, we identified the forests dominated with native *Quercus* species (212 plots that represent 84 800 ha of total forest area). Then diversification and improvement of *Quercus* dominated forests was carried out in two types of mature forests with quadratic mean diameter over and below 41 cm. To improve the resilience of mature *Quercus* dominant forests with mean quadratic diameter greater than 41 cm (84 plots that represent 33 600 ha of total forest area), we underplanted *Sorbus* spp. and *Prunus avium* every 5 years, with planting density of 200 trees/ha. It mainly aimed to support long-term integration of these species in mature and protective *Quercus* dominated forest stands. As for *Quercus* forests with mean quadratic diameter lower than 41 cm (128 plots that represent 51 200 ha of total forest area), we increased the probability of thinning of larger diameter trees (thinning from above) to 100%. The increase in probability of the thinning from above, aimed to facilitate the removal of damaged trees to support establishment of new regeneration of *Quercus*, *Sorbus* and *Prunus* species. The new regeneration was established to enhance biodiversity, improve soil conditions, and maintain the microclimate in these selected forests. The establishment of new regeneration was done mainly via planting *Quercus*, *Sorbus* and *Prunus* species with densities of 5000 trees/ha and 200 trees/ha respectively for both *Sorbus* and *Prunus*.



# PROJECTION RESULTS

## EFISCEN-Space

### Growing stock

Under baseline (BAU) and diversification of *Quercus* forests (Scenario 2) scenarios, the growing stock ( $\text{m}^3/\text{ha}$ ) was the highest with an average of  $294 \text{ m}^3/\text{ha}$  (BAU) and  $296 \text{ m}^3/\text{ha}$  (Scenario 2) respectively, over the 30-year projection (Figure 3). In the replacement of *Populus* scenario (Scenario 1), the growing stock had a decreasing trend in comparison to its initial state (decreased to  $289 \text{ m}^3/\text{ha}$  in 2055). These differences were mainly driven by underplanting measures carried out in Scenario 2. The underplanting with *Quercus*, *Sorbus* and *Prunus avium* (grouped as short-lived broadleaves) resulted in higher density of trees which increased growing stock volumes over time. As Scenario 1 focused on replacing *Populus* plantations to mix *Quercus* dominated forests to increase the forest diversity and resilience, the restoration measures required intensification of cuttings in poplar forests on calcareous fluvisols soils that were susceptible to changes in the groundwater table levels. Considering that the poplar plantations were replaced by planted small diameter size trees *Quercus*, *Sorbus* and *Prunus avium* (grouped as short-lived broadleaves), their contribution to growing stock volumes is not immediate. Therefore, the fluctuation of growing stock was strongly affected by the applied cutting and planting regimes.

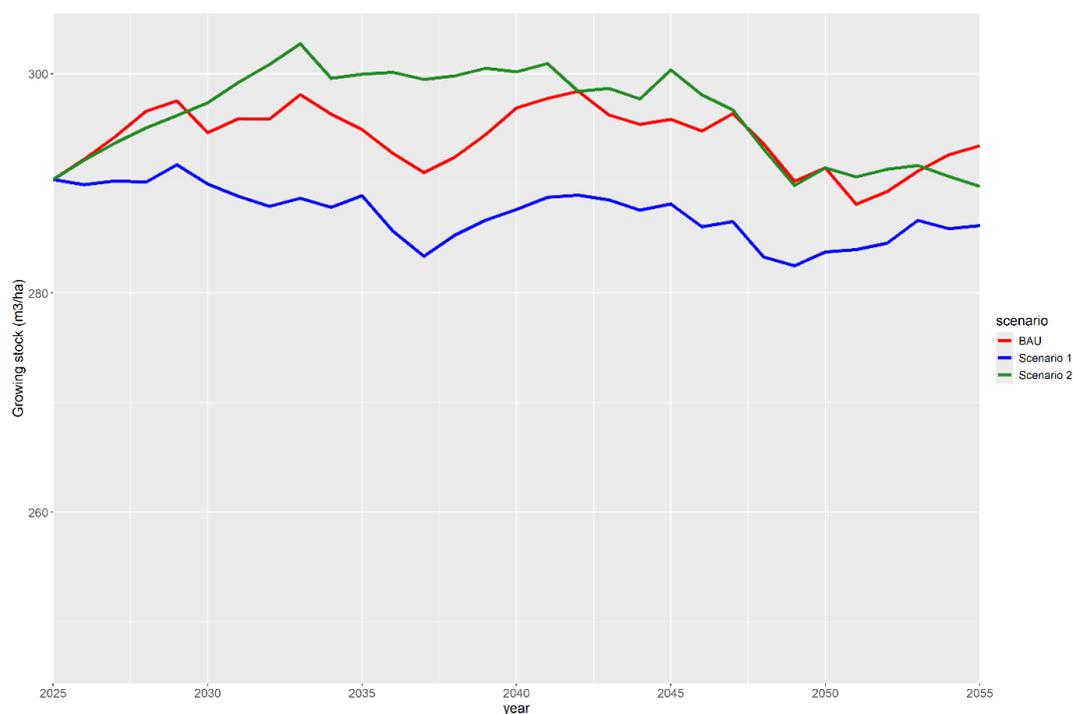


Figure 3. Growing stock ( $\text{m}^3/\text{ha}$ ) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

Considering that forest grows continuously, for all three scenarios more trees and thus volume was found in the larger diameter classes with dominant diameter class of 60–70 cm (Figure 4). In addition to the natural ingrowth which was dominated by long-lived broadleaves in smaller diameter classes (0–20 cm), the underplanting trees like *Quercus spp.*, *Sorbus spp.*, *Prunus spp.* (grouped as short-lived broadleaves) in Scenario 2 resulted in slightly higher volumes in the diameter classes 0–10 and 10–20 cm (increased by 0.6 and 0.8 m<sup>3</sup>/ha, respectively). As for Scenario 1, where the change of forest composition was applied to selected *Populus* forests, it resulted in lower volumes of this species in diameter classes from 50 up to 100 cm in comparison to the baseline (BAU) scenario. With the largest differences in diameter classes 60–70 cm (decreased by 1.6 m<sup>3</sup>/ha) and 90–100 cm (decreased by 2.2 m<sup>3</sup>/ha).

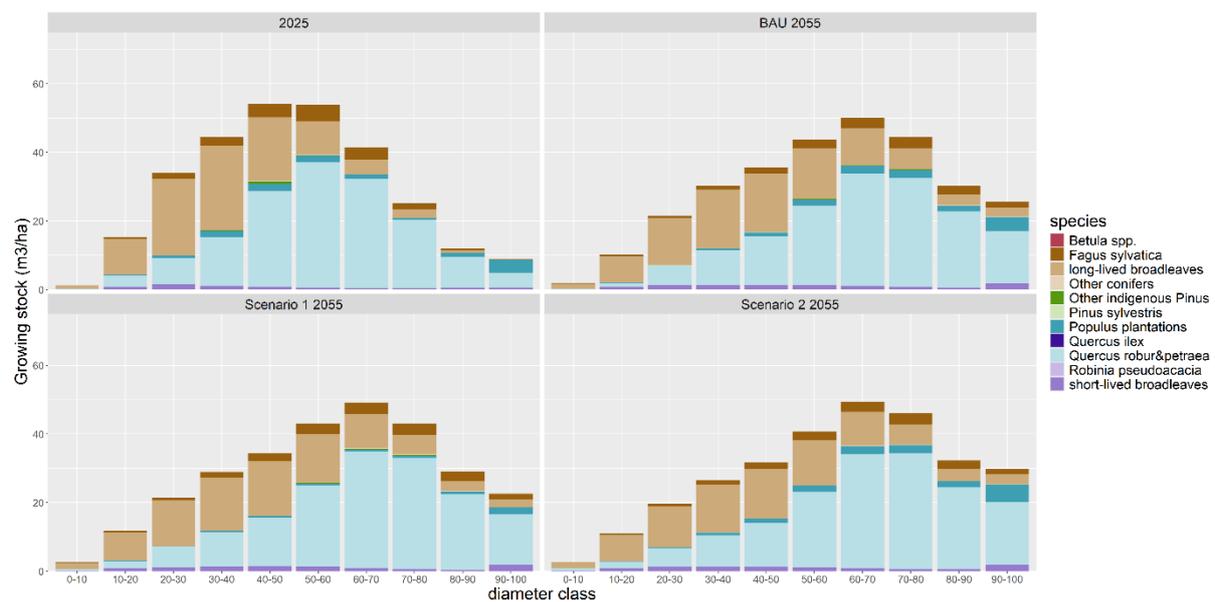


Figure 4. Growing stock (m<sup>3</sup>/ha) development per species over diameter classes (cm) from 2025 till 2055 for the three different scenarios.

## Increment

Under the diversification of *Quercus* forests (Scenario 2), the gross increment volume (m<sup>3</sup>/ha) was the highest in comparison to other scenarios due to underplanting of the accompanying species (Figure 5). However, the increment development showed a slightly decreasing pattern after the first 15 years (decreased by 0.25 m<sup>3</sup>/ha). Whereas for Scenario 1, the decrease of the gross increment was similar to the baseline scenario, from the initial 6.14 m<sup>3</sup>/ha to 5.75 m<sup>3</sup>/ha by 2055. As gross increment (tree growth) was affected by harvest and natural tree mortality, the steeper decrease in 2040 reflected applied cutting regimes.

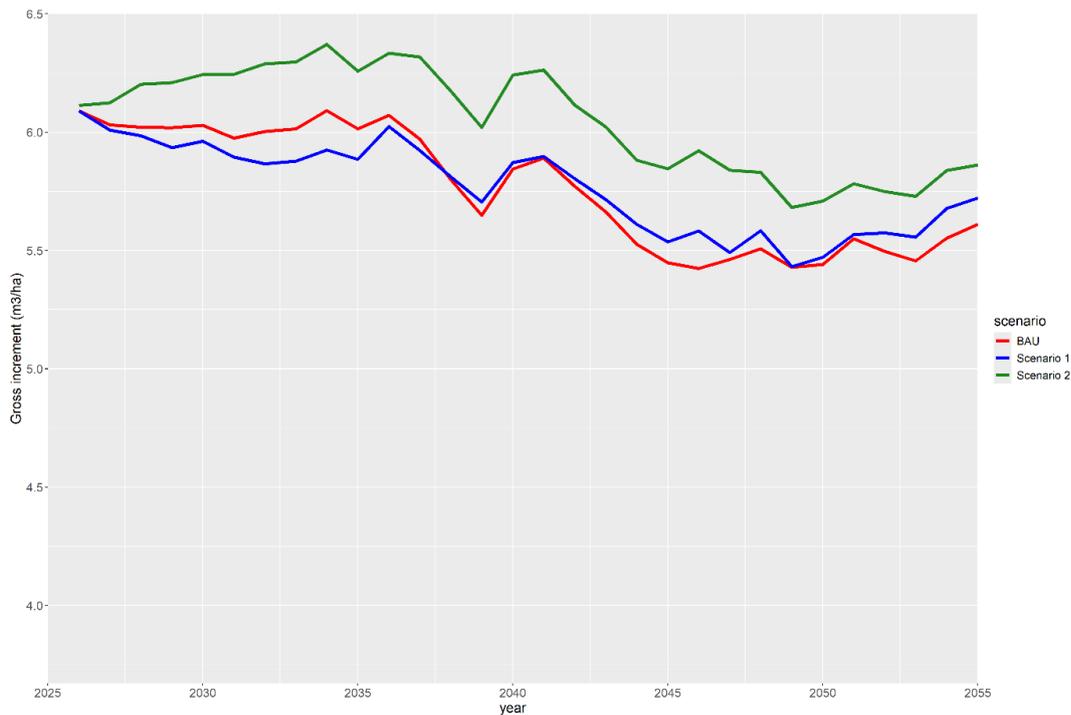


Figure 5. Gross increment ( $m^3/ha$ ) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

## Harvest

As trees grew into the harvestable thresholds applied in the scenarios, the wood harvest fluctuated with more harvest observed in certain years, e.g. peaks approximately every 10 years (Figure 6). In comparison to Scenario 1 and baseline, the mean annual harvested volume was higher by  $0.44 m^3/ha/year$  in Scenario 2. Since Scenario 2 applied diversification of *Quercus* forests, the underplanting of trees positively affected forests that reached their harvestable thresholds faster than in the other scenarios. As for Scenario 1, the harvested volumes were similar to those observed in the baseline although due to higher cutting intensity of *Populus* species and volume build-up (when trees reached harvestable volume), harvest increased during certain years.



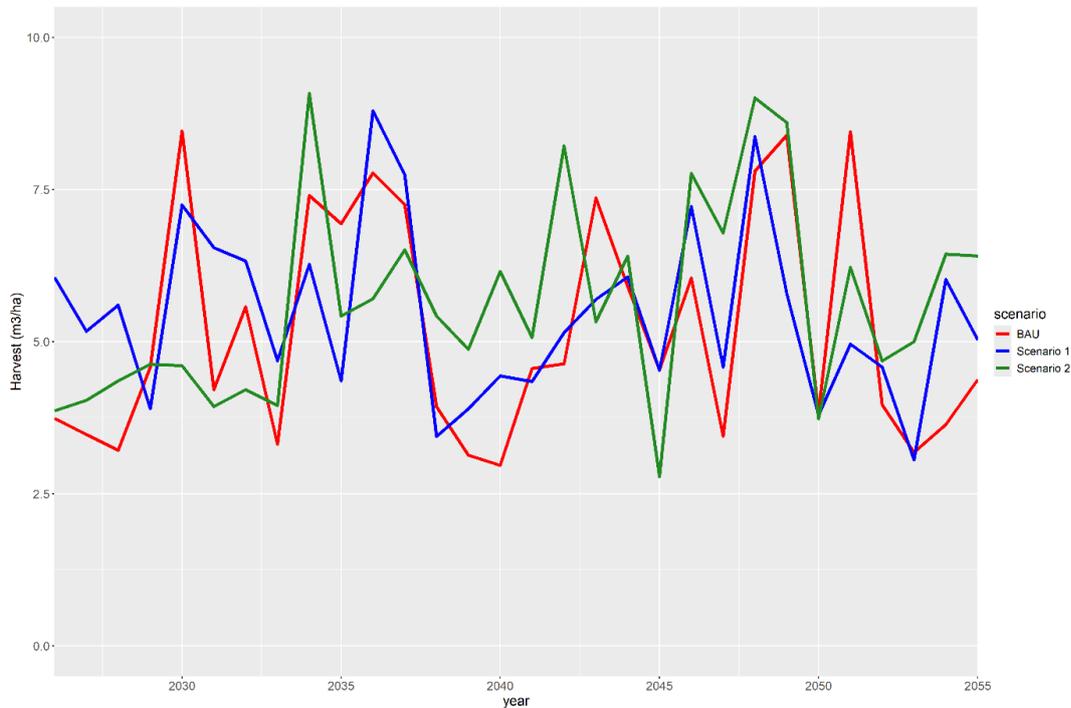


Figure 6. Harvested volume ( $m^3/ha$ ) development from 2025 till 2055 for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

## Mortality

Mean mortality showed similar patterns across all three scenarios BAU, Scenario 1 and Scenario 2, with the highest mortality in diameter class 20–30 cm ( $0.081 m^3/ha$ ,  $0.079 m^3/ha$  and  $0.075 m^3/ha$ , respectively) and its gradual decreased with larger tree sizes (Figure 7). In difference, when applying the underplanting measures like in Scenario 2, the increase of trees density in the first diameter class (0–10 cm) resulted in higher mean mortality ( $0.045 m^3/ha$ ). The increase in mortality was a result of self-thinning and competition for space between planted trees of *Quercus*, *Sorbus sp.*, *Prunus sp.* (grouped as short-live broadleaves).

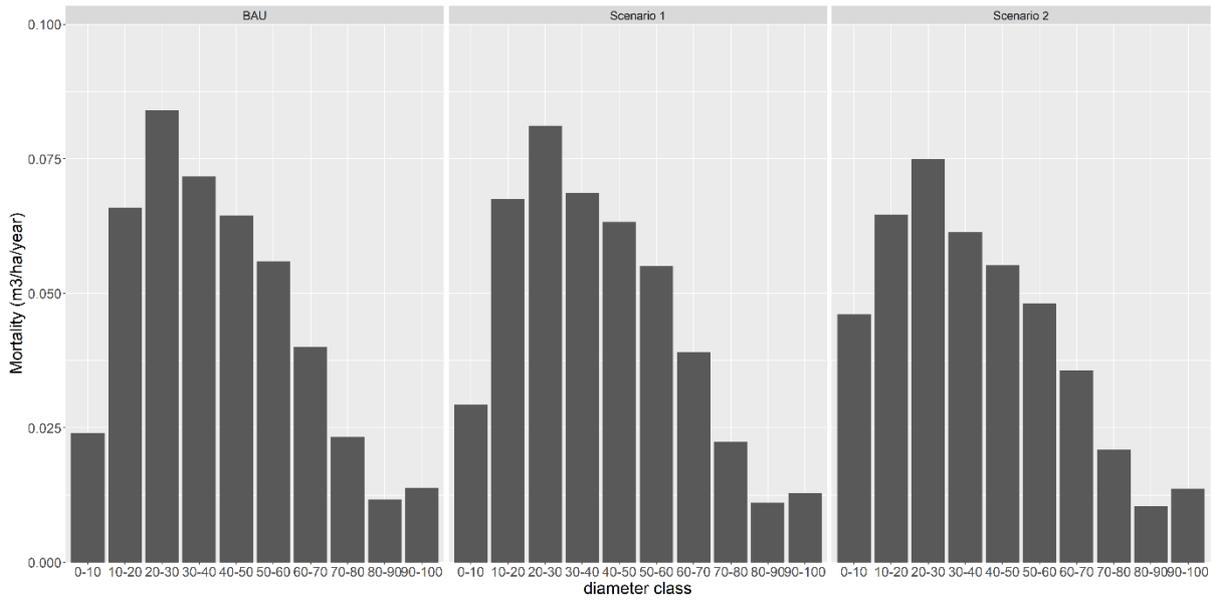


Figure 7. Mean mortality (m<sup>3</sup>/ha/year) development over diameter classes (cm) for the three different scenarios. Here mortality is estimated as an average 30-year simulation (from 2025 till 2055).

### Gini index

For all three scenarios structural heterogeneity (Gini index) was initially below 0.50 which indicated more homogenous (less complex) forest structure (Figure 8). As under Scenario 2 diversifying measures were applied, the increase in forest structural diversity increased from the initial 0.45 to 0.59 within 30-years. However, as smaller size trees were affected by other forest dynamics like growth and mortality the structural diversity started to stabilize by 2045.

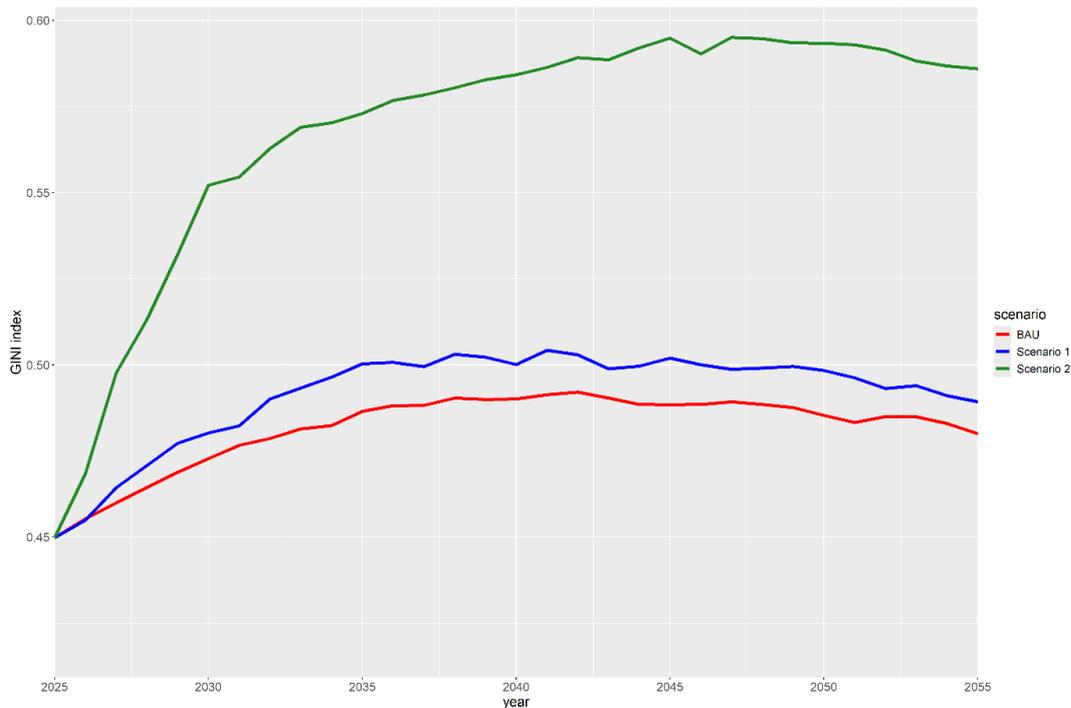


Figure 8. Gini index (inequality index) development for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2.

## Soil organic carbon

As soil organic carbon (SOC) was affected by the response of forest to varying restoration scenarios which were used for spin-up in Yasso15 (soil carbon model), the starting conditions differed for all three scenarios (Figure 9). With the highest SOC of 192 ton C/ha under Scenario 2 and the lowest of 187 ton C/ha in BAU. The differences in SOC were mainly driven by the varying amount of the litterfall which fell on the forest floor and decomposed, enriching soil carbon pools. More litterfall was accumulated in Scenario 2 due to higher density of trees which were planted to enrich *Quercus* forest stands. Whereas under BAU, the forest management followed current patterns of harvesting and excluded any additional planting measures. As for Scenario 1, where more trees were harvested, the patterns were similar to Scenario 2 which indicated that cuttings stimulated litterfall input to the soil. In general, SOC was sensitive to changes in aboveground biomass but still showed the increasing patterns by the end of 2055.

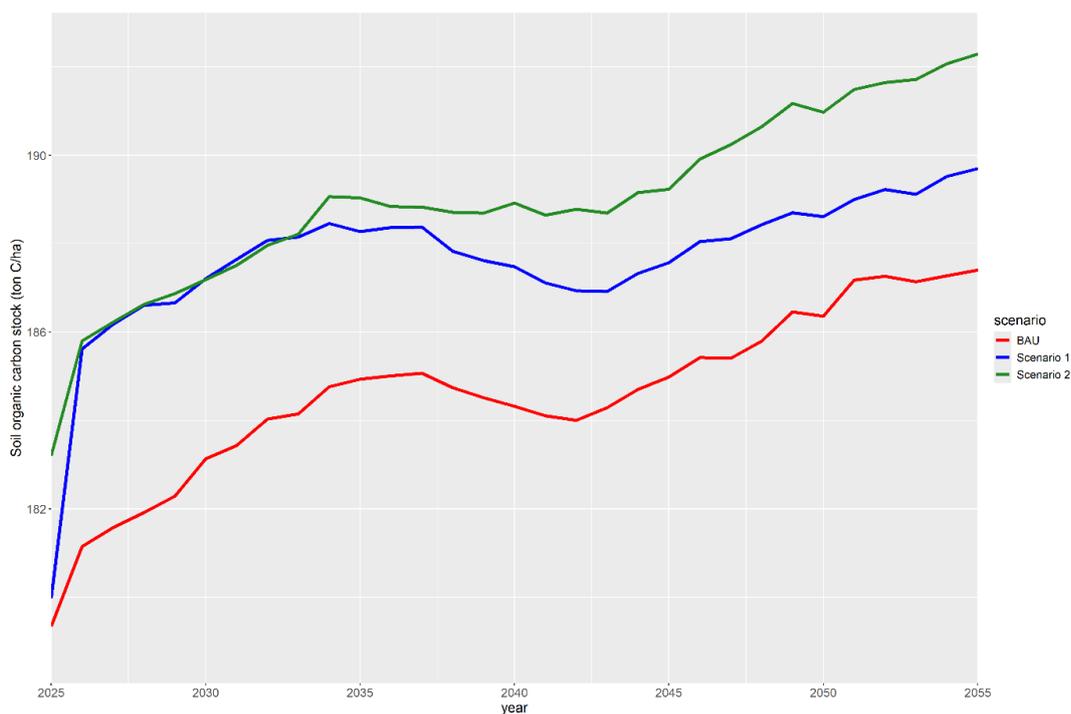


Figure 9. Soil organic carbon (SOC; ton C/ha) development for the three different scenarios. In red BAU scenario, in blue Scenario 1 and in green Scenario 2. The SOC was simulated using Yasso15 model (Järvenpää et al., 2018) coupled with EFISCEN-Space.

# KEY FINDINGS

In the Croatian side of the cross-border demo with 182 400 hectares of simulated forest area (represented by 456 NFI plots), the replacement of *Populus* plantation located on calcaric fluvisols soils was applied on 20 plots (8 000 hectares; 4% of total simulated area). Meanwhile, the diversification and improvement of *Quercus* dominated forests was carried out on 212 plots (84 800 hectares; 46% of total simulated area). Therefore, the restoration measures in both restoration scenarios were applied only to selected forests that were either highly susceptible to changes in groundwater table levels or required strengthening of biodiversity and resilience.

## Key finding #1

Replacement of *Populus* plantations on calcaric fluvisols soils which are highly susceptible to changes in the groundwater table levels (Scenario 1) resulted in increase of harvested wood volumes in upcoming 15 years (period 2025–2040) which consequently lowered the growing stock and increment volumes in those years.



## Key finding #2

Diversification of *Quercus* dominant forests by underplanting measures (Scenario 2) had an overall positive effect on the structural forest complexity and soil organic carbon (SOC) stocks within the next 30 years. It also resulted in higher availability of forest resources (e.g. growing stock, increment volumes, and to some extent harvested wood volumes).



## Key finding #3

All scenarios showed relatively positive development of the resources and biodiversity metrics (such as soil organic carbon (SOC) stocks and forest structure diversity index) over time. However, the development of the forest started to become stable from 2045 onwards which slowed down further improvement of restored forests.



# RECOMMENDATIONS

## Takeaway #1

Replacement of *Populus* plantations can support improvement of forest resilience and enhance diversification of forest composition to more future suitable species. However, it does not have immediate positive effects on the development of forest resources and structural diversity.



## Takeaway #2

Diversification of mature *Quercus* dominated forests through underplanting and change of forest management positively affects the development of more diverse and structurally complex forests. It also results in higher availability of resources like growing stock volumes and available harvested wood volumes in the long term.



## Takeaway #3

To maintain growing stock volume development and structural diversity of forest, forest management must be also considered, including both cuttings and underplanting which could regulate and sustain the resources in the long-term. At average restoration costs of 5 000 Euro/hectare (see Croatia-Serbia cross-border workplan v2.0), the total costs of the 92 800 hectare would amount to 464 million Euro in total for coming decades.



# REFERENCES

Feliciano, D., Franzini, F., Schelhaas, M.J., Haltia, E., Bacciu, V., Boonen, S., Filipek, S., Häyrinen, L., Lindner, M., Menini, A., Nieberg, M., Ofoegbu, C., Peltoniemi, M., Stancioiu, T., Staritsky, I., Uzquiano, S., Wiersma, H. (2025). Decision rules, parameters, and narratives for modelling. ForestPaths project deliverable D1.3.

Filipek, S. et al. In prep. EFISCEN-space, a large scale high resolution European forest resource model based on national forest inventory tree data. General description and model concepts. Manuscript.

Järvenpää, M., Repo, A., Akujärvi, A., Kaasalainen, M., Liski, J. 2018. Soil carbon model Yasso 15: Bayesian calibration using worldwide litter decomposition and carbon stock data. Manuscript in preparation (version 25 June 2018).

König, L. A., Mohren, F., Schelhaas, M. J., Astigarraga, J., Cienciala, E., Flury, R., ... & Nabuurs, G. J. (2025). Combining national forest inventories reveals distinct role of climate on tree recruitment in European forests. *Ecological Modelling*, 505, 111112.

Nabuurs, G. J., Werf, D. V. D., Heidema, A. H., & Wyngaert, I. V. D. (2007). Towards a high resolution forest carbon balance for Europe based on inventory data. In *Forestry and climate change* (pp. 105-111). Wallingford UK: CABI.

Schelhaas, M. J., Hengeveld, G., Filipek, S., König, L., Lerink, B., Staritsky, I., ... & Nabuurs, G. J. (2022). EFISCEN-Space 1.0 model documentation and manual.

Schelhaas, M. J., Hengeveld, G. M., Heidema, N., Thürig, E., Rohner, B., Vacchiano, G., ... & Nabuurs, G. J. (2018). Species-specific, pan-European diameter increment models based on data of 2.3 million trees. *Forest Ecosystems*, 5, 1-19.

